Physics Processes to be simulated

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Introduction

The current electroweak data favor a light Higgs boson of mass less than 255 GeV/c^2 at 95% confidence level [1]. A first muon collider is thus expected to have individual beam energies ranging from 50 GeV/c to 250 GeV/c, the latter extending beyond the threshold for the production of top quarks. The machine with beam energies in the range of 50 GeV/c would be capable of exploring the direct s channel production of Higgs bosons in the mass range 100 GeV/c^2 and above. The s channel production cross section of Higgs bosons is enhanced by a factor exceeding 40,000 for Muon Colliders over electron-positron colliders since the Higgs boson production cross section goes as the mass of the beam particle squared. The width of a Higgs boson of mass $\approx$ 110 GeV/c^2 is of the order of a few MeV/c^2 [2]. It is possible to calibrate the energy of a muon collider to a few parts per million from bunch to bunch using $g-2$ spin precession of the muons [3]. This will permit a detailed scan of the Higgs resonance. Muon Colliders should thus be capable of measuring the mass and width of the Higgs boson to unprecedented accuracy. A measurement of the branching ratios of the Higgs boson to various final states would enable us to distinguish the standard model Higgs boson from its Minimal Supersymmetric Model counterparts. At the energies associated with the Higgs factory Muon Collider, the showers produced by the electrons from the decay of the muons (there are 3.2×10^6 decays per meter at an energy of 50 GeV per beam and an intensity of 10^{12}) produce low energy photons with energies below the pair production threshold of 1 MeV that are at wide enough angle to enter the detector. They produce knock-on delta rays in the silicon detector in enough numbers to make pattern recognition difficult. The photons also produce neutrons by absorption in nuclei at the giant dipole resonance. The neutrons in turn diffuse into the detector and cause energy deposition by scattering against protons.

One of the attractive features of the muon collider is its ability to reach high center of mass energies (in excess of 4 TeV). At these energies, high energy Bethe-Heitler muons are produced in the showering of the decay electrons that make it past shielding and deflector magnets into the detector and deposit energy in the calorimeter via catastrophic bremsstrahlung. These Bethe-Heitler muons are out of time with the event. One of the challenges facing the detector simulation is to investigate the possibility of eliminating the confusion produced by these Bethe-Heitler muons by a judicious use of pattern recognition in a segmented calorimeter with an accurate timing capability.

In summary, the simulation challenge facing the muon collider collaboration is far more complicated than the one facing the electron-positron collider collaborations since we not only have to design a detector that is optimized for a variety of signal processes; we have to simultaneously optimize it to reject the expected backgrounds that are energy dependent. The results from such a simulation effort have to be obtained on a time scale of the next few years so that one can show that both muon cooling and muon physics are feasible. Only then will the muon collider be seen as a viable option for High Energy Physics.

Physics processes to be simulated

Members of the Muon Collider collaboration met with approximately 20 theorists on May 22-23, 1998, to discuss physics opportunities and physics simulation issues for the muon collider. The result of this workshop was a strong consensus on a priority list of physics processes for GEANT-level simulation. This list is summarized below.

1. $\mu^+\mu^- \rightarrow$ Higgs $\rightarrow b\bar{b}$. An s channel Higgs factory is a prime physics opportunity for a first muon collider. For Higgs mass below 135 GeV/c^2, Fig. 1 shows that the dominant decay mode of a Standard Model Higgs is to $b\bar{b}$. The priority goal for physics simulation

is to demonstrate the feasibility of measuring the s channel Higgs resonance for a 100 GeV Standard Model Higgs via the $b\bar{b}$ decay mode.

Another priority item is to examine the prospects for measuring the other significant Higgs decay modes. Fig. 1 shows that the branching fractions to $c\bar{c}$, gg, and $\tau^+\tau^-$ vary from 2% to 8% for a Standard Model Higgs. The figure also shows that these branching fractions are sensitive to Standard Model parameters; by the same token these branching fractions are important probes of supersymmetry and other forms of new physics.

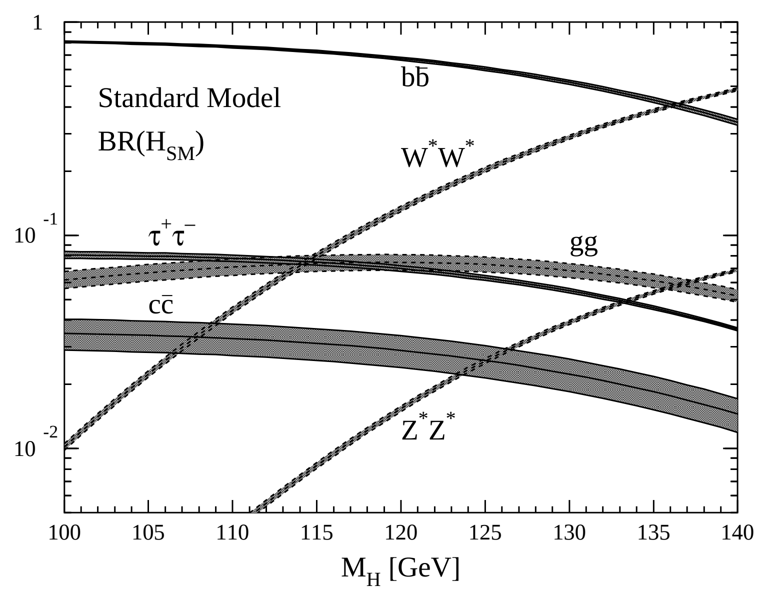

FIG. 1. *Branching ratios of the dominant decay modes of the SM Higgs particle [4]. All relevant higher order corrections are taken into account. The shaded bands represent the variations due to the uncertainties in the input parameters:* $\alpha_s(M_Z^2) = 0.120 \pm 0.003$, $\overline{m}_b(M_b) = (4.22 \pm 0.05)$ *GeV*, $\overline{m}_c(M_c) = (1.22 \pm 0.06)$ *GeV*, $M_t = (174 \pm 5)$ *GeV*.

2. **Basic processes for luminosity monitoring.** At existing lepton colliders luminosity is monitored via measurement of small angle Bhabha scattering, which has a large cross section. At the muon collider, Bhabha muons with forward or backward polar angle less than 20° will encounter the tungsten beam shielding. Thus a key physics issue is to determine the best strategy for luminosity monitoring at the muon collider, and to demonstrate feasibility by detailed simulations. At least three strategies need to be investigated:

   - **Small angle Bhabha muons.** Even for beam energies as low as 50 GeV/c, there is significant penetration of the tungsten shielding by small angle Bhabha muons. It has been estimated [5] that instrumentation of the outer portion of the shielding may allow a practical luminosity monitor by detection of Bhabha muons with polar angles in the range $20^\circ \geq \theta \geq 5^\circ$.

   - **Larger angle Bhabha muons.** Another strategy is to measure Bhabha scattering at forward and backward polar angles greater than 20°, thus avoiding the beam shielding altogether. Fig. 2 shows the cross section for $\mu^+\mu^-\to\mu^+\mu^-$ scattering for angles greater than 20°, as a function of the collider energy. Also shown in the figure are the cross sections for all of the other dominant Standard Model processes. The figure shows that the Bhabha cross section after the 20° cut is at least 10 times larger than any other Standard Model process, provided that $\sqrt{s}$ is taken larger than 150 GeV/c to avoid the Z^0 resonance. Thus the resulting luminosity measurement would contribute no more than 25% of the statistical uncertainty in any Standard Model physics measurement. For $t\bar{t}$ threshold measurements the contribution to the statistical error is less than 10%.

   - Z^0 **resonance.** For purposes of an s channel Higgs factory, with Higgs mass in the range 90 GeV/c^2 $\leq m_h \leq$ 150 GeV/c^2, it may be possible to monitor luminosity from measurements of the Z^0 resonance, since the basic parameters are known from LEP to approximately 0.1% accuracy. Fig. 2 shows that this cross section dominates s channel Higgs production by between 1 and 3 orders of magnitude.

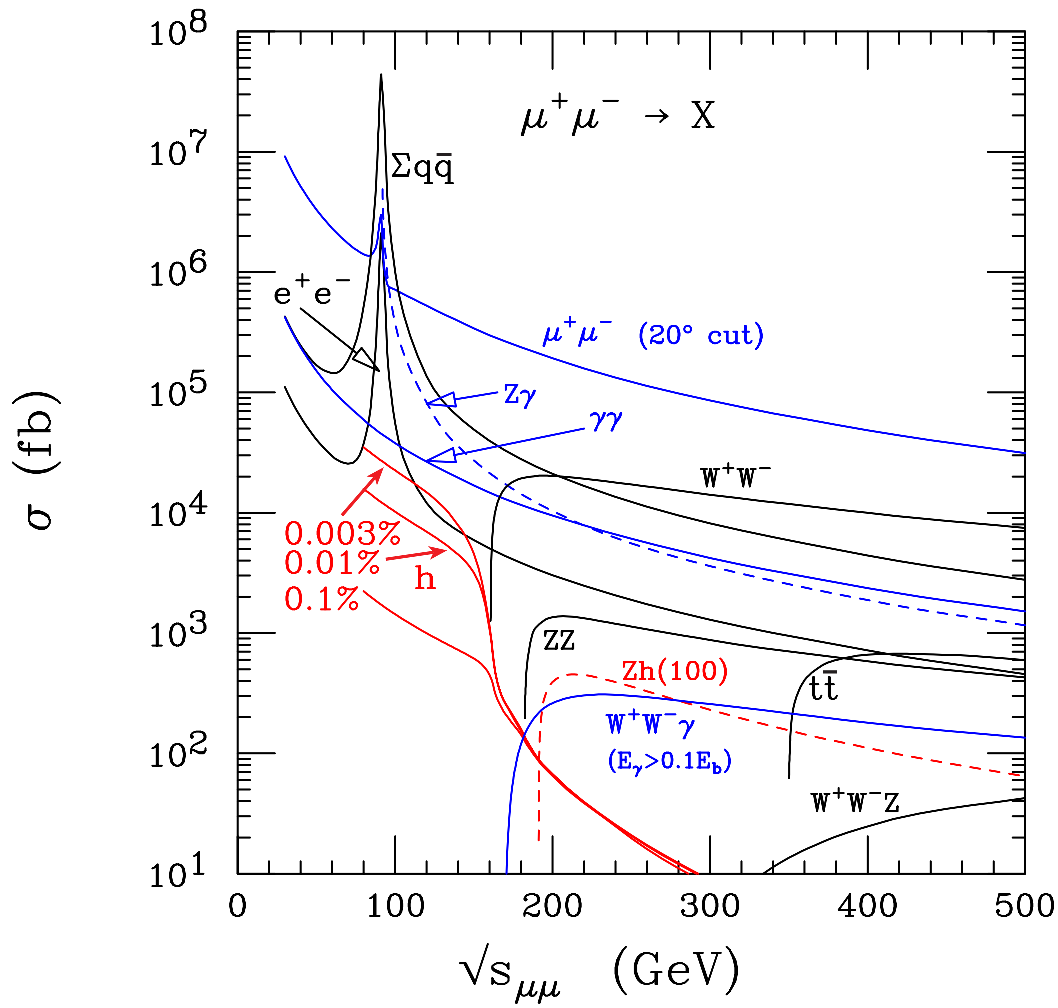

FIG. 2. *Cross sections for basic processes at a muon collider [6].*

3. $t\bar{t}$ **threshold.** The threshold region for $t\bar{t}$ pair production around $\sqrt{s}$=350 GeV/c can be scanned at both a muon collider and a future e^+e^- linear collider. However a muon collider has significant advantages (for comparable luminosities) over an e^+e^- machine for a precision scan, due to the better energy resolution of the beam and (more importantly) the absence of beam-beam interaction effects. Furthermore, Fig. 3

shows there is an additional advantage due to the relative suppression of initial state radiation for the muon collider.

Detailed physics simulations can determine to what degree these advantages for the muon collider are offset by the problem of beam decay backgrounds. Since V_{tb} will already have been measured with reasonable accuracy at the Tevatron and perhaps the LHC, it is also important to determine the likely precision of a V_{tb} measurement at the muon collider, combining the threshold scan with the $t\bar{t}$ momentum distributions and forward-backward asymmetry.

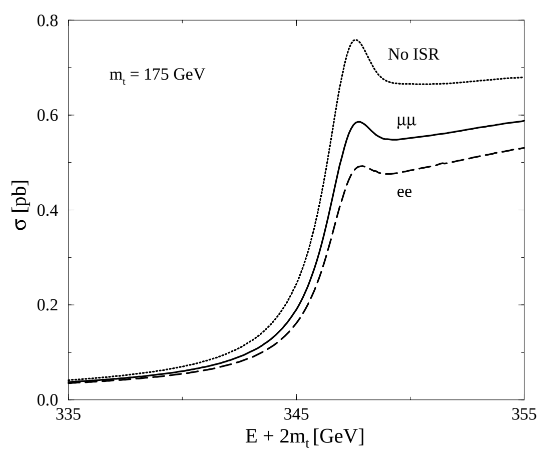

FIG. 3. *Comparison of e^+e^- and $\mu^+\mu^-$ initial state radiation effects on the a $t\bar{t}$ threshold scan [7].*

4. **Left-right asymmetry at the Z^0 resonance.** A first muon collider running at the Z^0 resonance could conceivably produce 50 million Z^0's per year [8]. The physics potential is further enhanced by the natural 20 to 30% polarization of both muon beams. In particular this degree of polarization should be sufficient for a high precision measurement of A_{LR}, the left-right asymmetry parameter [9].

5. **Supersymmetry.** A muon collider is in principle an excellent machine for precision studies of weak scale supersymmetry. Depending on $\sqrt{s}$ and the SUSY mass spectrum,

it may be possible to observe pair production of a dozen or more distinct superpartner particles. Although both the LHC and a possible e^+e^- linear collider will have significant reach for exploring weak scale supersymmetry, the muon collider has a number of unique capabilities. These are listed below; only the first two are priority items for simulations.

- **Heavy Higgs.** Supersymmetry predicts an extended Higgs sector, with additional CP even and odd scalars H and A, as well as a charged pair $H^{\pm}$. For a wide range of parameters these particles will be very difficult or impossible to observe at the LHC or a linear collider. However the s channel production of H and A may be observable at the muon collider. Since the location of the resonance peaks may not be known beforehand, it may be necessary to locate the peaks in the bremsstrahlung tail of the $b\bar{b}$ invariant mass distribution [8]. Detailed simulations are needed to see if this is feasible, and also to determine the prospects for separating the H and A resonance peaks, which may be separated by less than 1 GeV in energy.

- **Flavor dependence.** Precision supersymmetry studies at a muon collider will complement precision studies at a possible e^+e^- linear collider, and in addition offer the unique opportunity to measure lepton flavor dependent effects. The simplest and cleanest process for detailed simulations is smuon pair production. Fig. 4 shows the precision achievable by a perfect detector at a realistic luminosity.

- **Mass reach.** There are hints from precision data that at least part of the superpartner spectrum is very heavy, with masses > 1 TeV. In this case a 4 TeV muon collider may be essential to access these heavy particles.

- **Resonant sneutrino production.** If R parity is violated, it may be possible to observe s channel resonance production of the muon sneutrino.

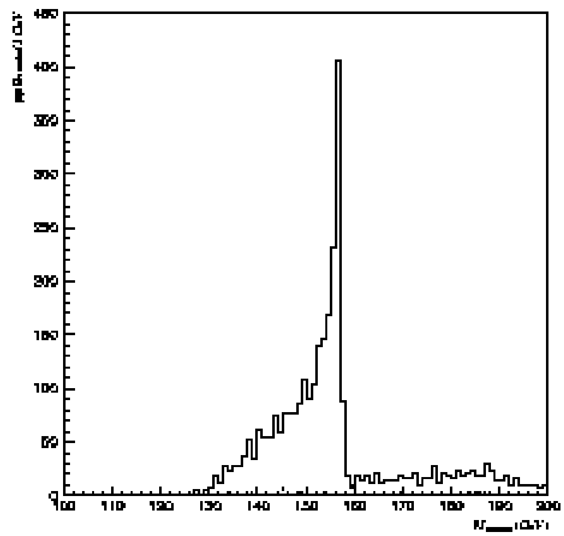

FIG. 4. *Dimuon production after cuts, 20 fb^{-1} at $\sqrt{s}$=600 GeV for a minimal supergravity point with 157 GeV/c^2 smuons [10]. The solid line is the total smuon signal, plotted versus the Feng-Finnell estimate for the smuon mass. The dashed line is the sum of the Standard Model backgrounds.*

Detailed simulations of the priority physics processes discussed above are absolutely essential for determining the actual physics potential for experiments at a muon collider. Taken together, these simulations will also address the most important detector issues in the muon collider enviroment, involving vertex tagging, calorimetry, and particle id. New physics which may manifest itself before the advent of the muon collider is likely to require similar detector capabilities to those highlighted by these simulations.

Backgrounds

The Muon Collider collaboration [5] [11] [13] has done extensive simulations using GEANT and MARS codes of backgrounds in the detector volume resulting from electrons showering in the beam shielding. The shielding design has been optimized as shown in Fig.5 to reduce the background level from soft photons in the detector area. Figure 6 shows the occupancy as a function of radius in a silicon detector for the three center of mass energies of 0.1TeV, 0.5 TeV and 4 TeV for pad sizes of $300 \times 300\,\mu m^2$. We have also simulated the energy deposition in a calorimeter from catastrophic brehmsstrahlung by Bethe-Heitler muons resulting from electron showers in the beam pipe. Figure 7 shows the trajectories of these muons in the detector neighborhood for a 100 GeV CoM collider. Figure 8 shows the energy deposit in the calorimeter for a 4TeV CoM collider detector with and without a 1 ns timing cut in the calorimeter. The Bethe-Heitler muons are out of time with respect to the event from the interaction region, due to their different path lengths. More details of the simulations done so far can be found in [13].

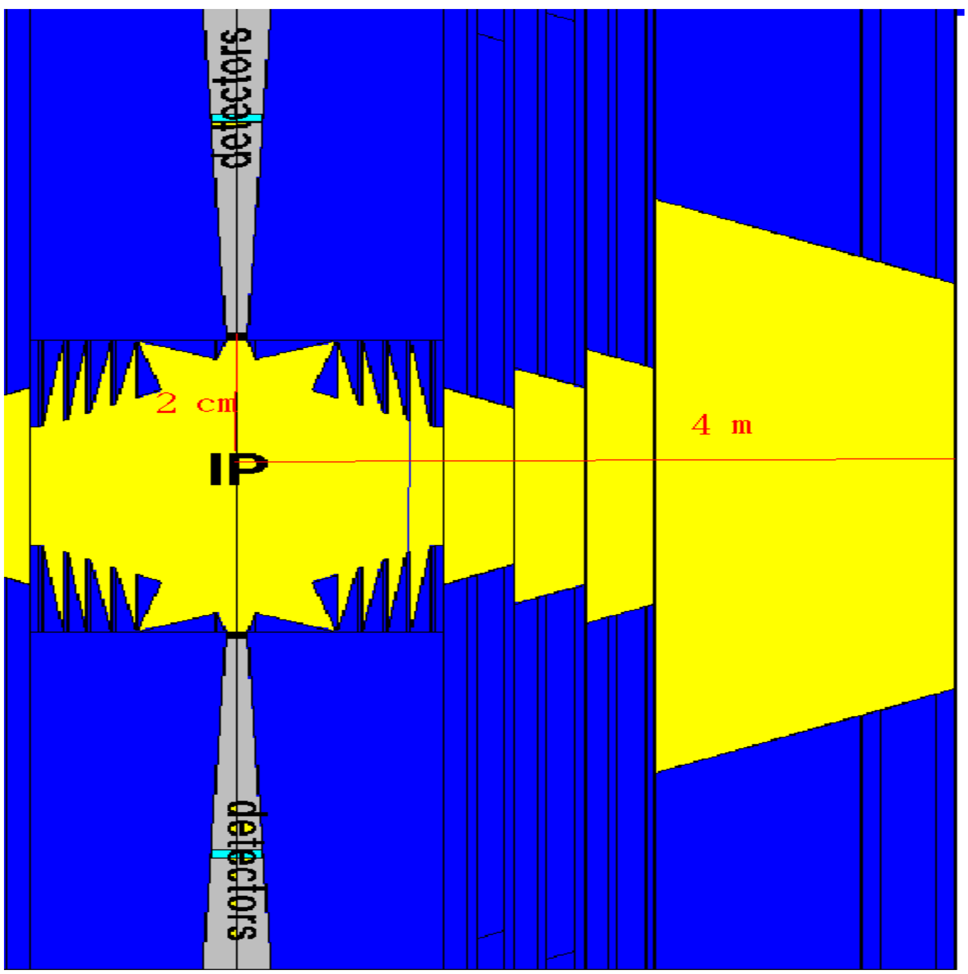

FIG. 5. *Detail of the tungsten shielding designed for the 50 + 50 GeV case. It is designed so that the detector is not connected by a straight line with any surface hit by decay electrons in both forward or backward direction. The picture extends out to radii of 6 cm and, on the right, to a distance 4 m from the IP. The dipole from 2.5-4.0 m is not shown.*

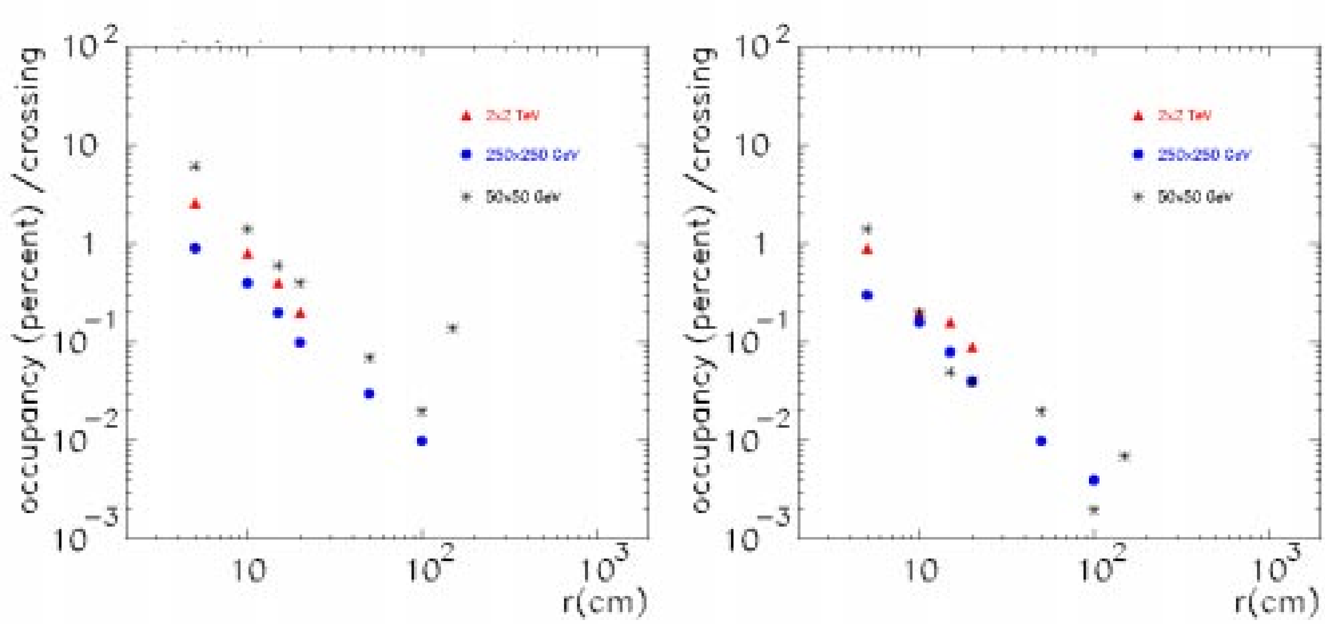

FIG. 6. *Occupancy for* $300 \times 300\,\mu\,m^2$ *silicon pads, as a function of the radius for the three energies studied. Left figure shows the total occupancy and the right figure shows the occupancy from hits resulting from charged particles.*

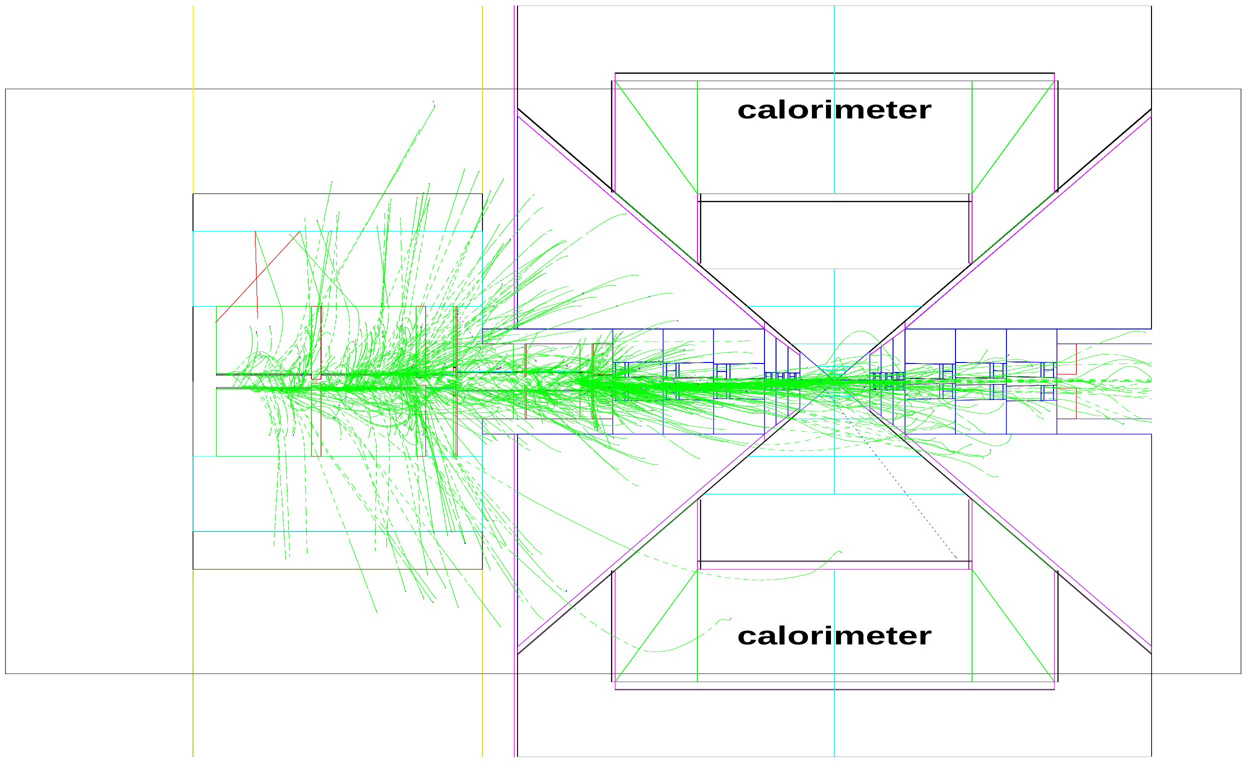

FIG. 7. *Trajectories of typical Bethe Heitler muons from their source in the shielding around the beam pipe to the detector for a 100 GeV CoM collider. Notice that* $< 0.5\,\%$ *of the tracks end in the calorimeter*

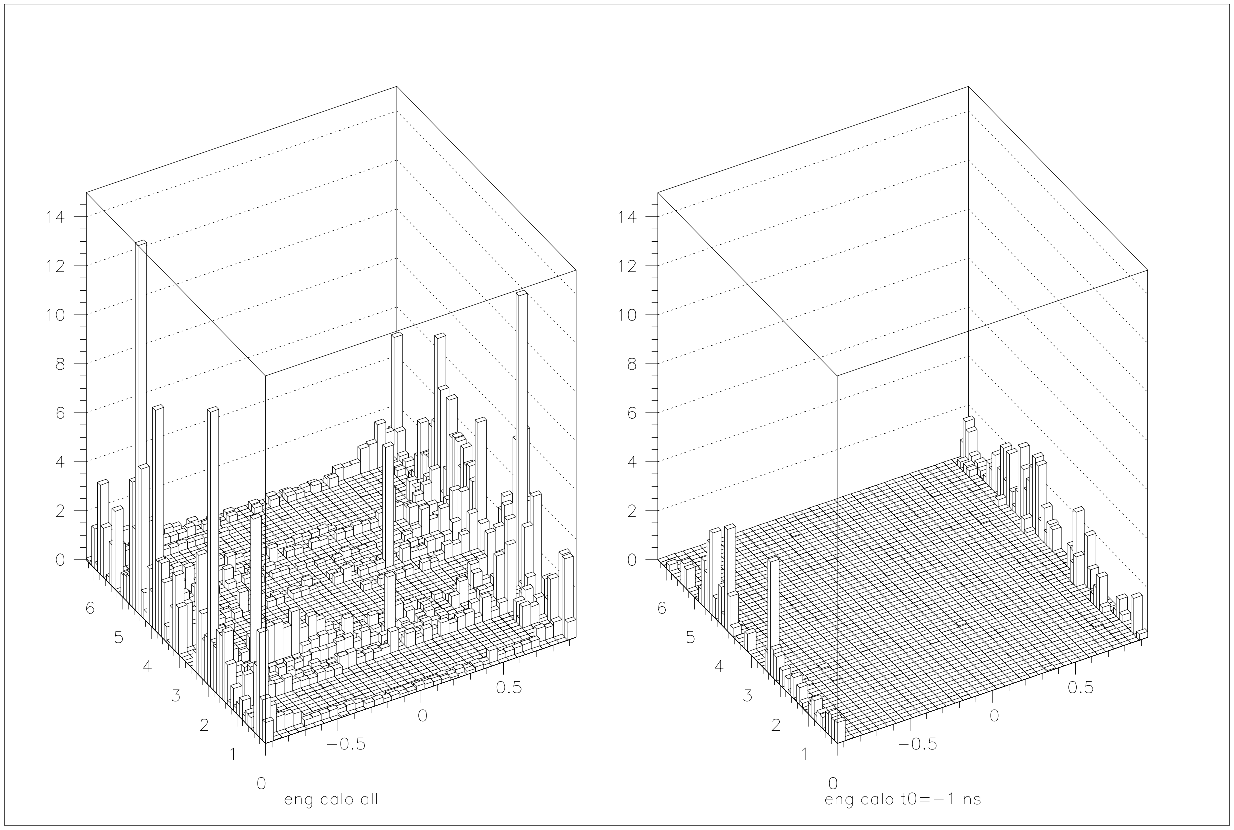

FIG. 8. *Left hand-side plot shows the energy deposition from Bethe Heitler muons vs. the cosine of the polar angle and azimuthal angles in the calorimeter for a 4 TeV CoM collider. Right hand-side plot shows the same distributions with a 1 ns timing cut.*

Physics questions to be answered and manpower needs

It is seen from the above discussion that the Muon Collider collaboration has done a significant amount of simulation and optimization to calculate and ameliorate the significant backgrounds present in the detector. However, we do not have a full GEANT simulation of the detector with backgrounds and a full pattern recognition of the events in the presence of the backgrounds.

The following outstanding questions remain: We have estimated the amount of effort needed to answer each question in parentheses.

- Can one optimize the lattice near the interaction region to reduce the backgrounds further? (2 man-years)

- Can one do b-tagging using silicon pixels with the large number of hits caused by the photon background? (1 m.y.)
- What is the efficiency *vs.* purity of b tagging? (1 m.y.)
- Can c-tagging be even contemplated? (0.5 m.y.)
- How can we design a fast vertex algorithm so that silicon readout can be attempted for only projective coincidences in a pixel micro-telescope? (1 m.y.)
- Will a TPC work at all energies as an outer tracker? (1 m.y.)
- What segmentation does the calorimeter need to have to pattern recognize Bethe-Heitler muons? (0.5 m.y.)
- What e/π ratio, linearity and resolution are necessary for the calorimeter? (0.5 m.y.)
- What calorimeters will permit the measurement of arrival times to 1 ns? (0.5 m.y.)
- How much distortion is there in the energies of jets and electrons as a function of background? (0.5 m.y.)
- Can one compute the pedestal energy deposits in the calorimeter resulting from the heavy neutron background which will vary as a function of the turn by turn muon intensity? (0.5 m.y.)
- Do we need a muon system? Or is it better to have a deeply segmented calorimeter which will pattern recognize muons as minimum ionizing tracks? (0.5 m.y.)
- Can one detect forward going muons from the interactions? (0.5 m.y.)
- How do we compare with the NLC in the physics channels outlined above which can be realized in both types of accelerator? (2 m.y.) This in essence addresses the

physics channels listed above. The time estimate if for the situation after the pattern recognition is in hand.

- Can one design a detector capable of operating at 0.1TeV,0.5TeV and 4 TeV at the center of mass without major modification? (0.5 m.y.)

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